National Defence

RESEARCH AND DEVELOPMENT BRANCH
DEPARTMENT OF NATIONAL DEFENCE CANADA

SUPERCONDUCTIVITY:

RECENT DEVELOPMENTS AND DEFENCE APPLICATIONS (U)

by
R.W. MacPherson
Directorate of Scientific Policy

CRAD-REPORT
NO. 1/88

Canada

11 MAR 1988 OTTAWA

UNCLASSIFIED

1

RESEARCH AND DEVELOPMENT BRANCH

DEPARTMENT OF NATIONAL DEFENCE

CANADA

Directorate of Scientific Policy

SUPERCONDUCTIVITY: RECENT DEVELOPMENTS AND DEFENCE APPLICATIONS (U)

By

R.W. MacPherson

CRAD REPORT 1/88

This paper represents the considered opinion of the author and does not necessarily represent the official views of CRAD.

APPROVED:

Chief, Research and Development

11 Mar 88
OTTAWA

UNCLASSIFIED

ABSTRACT

(U) The recent advances in superconductivity have led to much speculation about the possible applications of the new technology to all walks of life. In an attempt to determine what defence applications have realistic expectations of coming to fruition, a number of opinions solicited from defence scientists is summarized and reviewed along with information obtained from selected journal and magazine articles.

RÉSUMÉ

(NC) L'enthousiasme susité par les récentes découvertes réalisées dans la domaine des supraconducteurs a fait l'objet de beaucoup de spéculation concernant les applications possible à toutes sortes d'activités de la vie courante. Afin de determiner laquelles des applications pour la défense présentent des probabilités plus que raisonnable d'être réalisées, le present document critique et résume sommairement les opinions de certains scientifiques de la défense et aussi le contenu de articles spécifiques tiré de journaux et de revues.

A-1

TABLE OF CONTENTS

TABLES

SUPERCONDUCTIVITY: RECENT DEVELOPMENTS AND DEFENCE APPLICATIONS

Introduction

The 'recent breakthrough'

1. The recent discovery of a new class of superconducting materials has excited members of the scientific community with the possibility of discovering whole new mechanisms for producing the superconducting state and has aroused the technological community with the prospect of realizing many applications once thought impracticable. The heightened interest is due to the significantly higher temperatures at which superconductivity is achieved. The temperatures are high enough that cooling can be obtained with relatively inexpensive and easily produced, liquid nitrogen instead of the expensive and difficult to produce, liquid helium required for 'conventional' superconductors. For applications in space, active cooling may not even be necessary to reach the temperatures required by these new materials.

2. This paper is based on a number of ideas submitted by DRE and CRAD/HQ scientists who responded to a request from DGRD Pol to identify potential applications of the new superconductors to defence. Additional information came from a selection of magazine and journal articles. In such a rapidly moving field as this it is not possible to claim currency; rather this paper represents a snapshot of some of the information published by the end of 1987.

The potential impact on defence capabilities

3. The discovery of high temperature superconductivity could have an enormous impact on defence capabilities. Representatives from DARPA/ONR have said that it could be "overwhelming", comparable to the impact that the introduction of transistors had in the era of vacuum

tubes. In all walks of life, many applications that were once abandoned as laboratory curiosities may now be feasible and several others, which had been developed and fielded using liquid helium, show promise of being much cheaper and easier to obtain, thus opening their use on a much broader scale. Many of the commercial or civilian applications will have defence counterparts. Large and small scale applications such as computers, electronic devices, magnets, motors, and sensors are examples. Others products and devices of particular interest to the defence community include: batteries, bearings, electromagnetic guns and launchers, energy storage, free electron lasers, controlled thermonuclear fusion, generators, gyrotrons, magnetic shielding, propulsion systems, traveling wave tubes, and switches and energy storage devices for directed energy weapons, high powered lasers and nuclear simulations. Small scale applications of interest include optical, IR and microwave detectors, SQUID magnetometers, waveguides and antenna arrays. The projected performance capabilities of some applications appear almost unbelievable when viewed relative to today's standards. For example, a physicist in the U.S. National Security Agency has suggested the possibility of building a superconducting computer with the power of a Cray super computer in a package as small as one cubic foot.

Background

Original discovery

4. Originally discovered over 75 years ago in mercury, the phenomenon of superconductivity manifests itself by the complete disappearance of electrical resistance and the exclusion of magnetic fields from a number of materials when they are cooled below a critical transition temperature symbolically represented as T_c. Since 1911 when Onnes discovered the phenomenon, the continuing search for materials with progressively higher transition temperatures has resulted in a steady, linear increase in achievable T_c. By the end of 1986 the maximum obtained was 23.3 K.

Current applications

5. Applications of superconductivity using the older materials have included the creation of high magnetic fields for high energy physics, fusion research and nuclear magnetic resonance tomography; quantum interferometers used in detectors for research into biomagnetism and gravitational waves; and analogue electronics devices such as microwave detectors, signal processors and voltage references. The requirement for cooling with liquid helium has prevented the development of any fielded defence applications although DREP has explored the idea of using SQUIDs for magnetic anomaly detection in anti-submarine warfare. The main point to note is that, with the exception of nuclear magnetic imaging scanners used for medical diagnosis, most of the applications to date have been in laboratory based research tools used in other investigations.

Limitations of Current Superconductors

6. The requirement to cool conventional superconductors with liquid helium is the main limitation to their widespread use. From purely thermodynamical considerations alone it is 25 times cheaper to refrigerate to the 77 K of liquid nitrogen than it is to the 4.2 K of liquid helium. The inability to withstand high magnetic fields and to transport currents at high densities is another limitation of the early materials. The first superconducting materials discovered were elemental metals. These materials, called Type I superconductors, lose their superconducting properties in relatively weak magnetic fields (less than 0.12 tesla) or when carrying small electrical currents. The difficulty of making large magnets which remained superconducting in high magnetic fields restricted development of several applications. With the discovery of the so-called Type II superconductors in the 1950s, the critical fields under which superconductivity was still possible increased to tens of tesla. The type II materials, which offered the prospect of high current capacity and the production of high magnetic fields, have occupied scientists and engineers for the past 20 to 30 years. The principal materials used in high magnetic field technology are niobium titanium (NiTi), a ductile alloy that can be

readily formed into wires, and niobium tin (Ni_3Sn), which can support very large currents and high magnetic fields, but which has found limited use because of its brittleness. Niobium itself has found limited use in radio frequency cavities and niobium nitride (NiN) is used in electronics.

Recent developments

New class of superconducting materials

7. In 1987 a dramatic change occurred when researchers discovered a new class of superconducting materials that exhibit transition temperatures near 40 K and 90 K. Some materials were reported with indications of transition temperatures at 240 K and up but these results have not yet been verified by independent laboratories. The work that has followed over the past year has largely been Edisonian in approach. Many different variations on the recipe have been systematically explored, but no clear understanding of why some things work and others do not has yet emerged. Theoreticians have yet to develop a satisfactory explanation for the high transition temperatures or for the existence of superconductivity itself in these new materials. In the meantime there is little guidance as to what to try next. Until this basic difficulty is overcome many feel that it is inappropriate to think in terms of developing actual applications at this point in time. Nevertheless, the first crude electronic devices making use of superconductors could well appear within a year.

Properties

8. The new superconducting materials are mixed metal oxides that exhibit the mechanical and physical properties of ceramics. The large number of the so-called high temperature superconductors (HTSCs) now known are variations of two basic types:

a. $(La_{1-x}M_x)_2CuO_4$, where x=0.1 to 0.5 and the metallic elements, M, = calcium (Ca), strontium (Sr), or barium (Ba). Lanthanum (La) is the base rare earth element. These materials were discovered first and have transition temperatures in the range 30 K to 40 K.

b. $RBa_2Cu_3O_{9-x}$, where x=2 to 2.4 and the rare earths, R, = yttrium (Y), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), or lutetium (Lu). These materials exhibit transition temperatures of 90 K to 95 K. They are also known as 1-2-3 compounds by virtue of their composition, whose metallic elements appear in the ratio of one rare earth (R) and two barium (Ba) to three copper (Cu) atoms.

9. As ceramics the materials are brittle and, although strong, are susceptible to stress cracking. They lack the ductility of the niobium alloys and so cannot be formed into wires by normal processes. Plasma spraying or other coating methods on host materials such as aluminum or copper will have to be developed.

10. The chemical properties of the various 1-2-3 compounds are similar. The materials are oxygen deficient oxides with a rough perovskite crystal structure. They lose oxygen easily when heated to 550 C in vacuum, change from the orthorhombic to tetragonal structure and lose their superconducting properties. The process is reversible when they are reheated at similar temperatures in an oxygen atmosphere.

11. One of the more peculiar aspects of the materials is the way in which they reflect light. No matter how smoothly they are polished their surfaces still appear dull. The reflecting properties of solids reveal much about the distribution of their electrons. Metals reflect a lot of light but these materials reflect little and their electron distributions, determined by other means, resemble those of insulators rather than conductors.

12. As superconductors, the new materials belong to the Type II group although some important differences exist. The transition to the superconducting state, for example, occurs over a range of several degrees instead of sharply. The superconductivity is anisotropic: the critical currents depend on the direction in which they pass through the crystals. The critical currents are also very low compared to those available in conventional

superconducting materials. On the other hand, the critical magnetic fields appear to be very high. Extrapolation of the measurements of the critical fields for the 1-2-3 compounds indicate that at low temperature the limits of the upper values lie between 80 and 320 tesla. To put this into perspective, the energy density in a 150 tesla field is about one quarter that of dynamite. At such levels, however, the forces generated between the field and the current in the wires of the magnet producing it are so large that it would be difficult to construct a magnet with sufficient strength to support them.

Limitations of the new materials
-- Unresolved problems
(Pacing problems/technical barriers)

13. The primary limitation in producing these materials is the lack of understanding of the reasons for their superconducting properties. Basic research is needed to understand why small details of the preparation of the new high temperature superconductors lead to dramatic changes in the characteristics of the materials produced. So far electron pairing as in BCS superconductors has been confirmed. Mechanisms proposed as being responsible for the pairing include:

(a) Phonon electron interaction as in BCS materials
(b) Plasmon (collective motion of electrons)
(c) Excitons (local polarization of electron orbitals)
(d) Magnons (spin fluctuations travelling through the lattice), and
(e) The Resonance Valence Band Theory of Anderson

Chemical and physical stability

14. The lack of basic understanding makes it difficult to modify the materials to obtain satisfactory physical and chemical properties. The brittleness of the current materials and their poor chemical stability present significant problems. The materials decompose quickly and are difficult to prepare in useful forms. When exposed to the air they react with water vapour, lose oxygen and revert to non superconducting materials. Their physical

and chemical stability under disturbance or transient conditions must be addressed. Stable and structurally sound materials with increased strength and fracture toughness are needed.

Material fabrication

15. As ceramics they are not easily fabricated into useful shapes by simple mechanical processes. Processing technologies must be developed and techniques found for producing, reliably and reproducibly, new high temperature superconducting materials that can be fashioned into structures such as thin films, wires, sheets, coils, etc., and that have adequate mechanical properties for their intended applications. Although there is hope that manufacturing methods developed for ceramics could be adapted for these new materials, the materials themselves are not yet suitable for engineering applications.

Low critical current

16. Even in the superconducting state there are limitations. While these materials remain superconducting in the presence of high magnetic fields, they are, as mentioned above, limited in the current density they can carry without reverting to normal conductors. The new superconductors consist of anisotropic crystalline grains: their electrical conductivity depends on the direction along the grains in which current flows. To achieve high current densities some alignment process may be necessary to ensure that individual crystal grains in the bulk materials are oriented along the same direction and brought into closer contact. Currently produced materials are porous. Their densities are only about 80% of the theoretical maxima for the known crystal structures and they must be made more dense. The low current carrying capacity is the main limitation to high power applications.

Contact resistance

17. Achieving good, low resistivity electrical contacts with the high temperature superconductors is not easy. Being ceramics, the materials are not amenable to welding

or conventional soldering techniques. Pressed indium or silver metal pads or evaporated noble metal coatings may provide solutions, but even then finding a way to make a contact that remains reliable over several temperature cycles between liquid nitrogen and room temperatures is a challenge.

Incompatibility with manufacturing methods for microelectronics

18. For small scale and low power applications there is an incompatibility between the production processes for superconducting materials and microelectronics. Superconductive ceramics must be heated during manufacture to high temperatures (900°C) which means that they cannot be assembled with other materials or components such as semiconductor devices until after they are fired. This limits design possibilities.

Need for refrigeration

19. Finally, there is still the requirement to cool the materials to liquid nitrogen temperatures. For some applications to be practicable, superconductors at room temperature and above will be necessary. There is hope that even higher transition temperature materials will be discovered. Materials with indications of transition temperatures above 90 K have been reported, but their superconductivity has only been tested indirectly. Some direct confirmation is needed.

Canadian activities in HTSC

20. Canadian activities are widespread. Researchers at Brock University produced the first Canadian paper on the new materials. McMaster University is concentrating on the synthesis and physical structure of the materials and on measurements of the energy gap and phonon structure, as well as strong phonon coupling theory. NRC was one of the first laboratories to report on the basic structure. The TRIUMPH facility UBC, in collaboration with Bell Laboratories, has looked at muon spin rotation measurements of the penetration depth of magnetic fields into the superconductors. Basic research is under way at Chalk River, University of Toronto, Queen's, RMC Kingston,

Sherbrooke and Alberta. In addition, considerable interest is being shown by government agency and industrial laboratories at Alcan, Atomic Energy of Canada Limited, Canadian Thin Films, Canadian Wire and Cable, Northern Telecom Electronics, and Ontario and Québec Hydro.

International HTSC activities

Europe

21. Europe's historical strengths in basic research and industrial development are being applied to the new superconductors. Corporations foster and maintain the European expertise in superconductivity. The Brown Boveri Corporation in West Germany, for example, is a manufacturer of superconducting magnets. Indeed, the recent advances began with Bednorz and Muller's work at the IBM Laboratory in Zurich.

India

22. India is reported to have established an organization, led by Prime Minister Gandhi himself, to investigate what its involvement in superconductivity research should be. Indian Science Council President, C.N.R. Rao has proposed that a national science and engineering foundation examine high temperature superconductivity as one of several frontier technology areas.

Japan

23. The Japanese have recognized for some time the potential importance of high temperature superconductors. In the early 1980s the Ministry of Education, Science and Culture established the 'New Superconducting Materials' project whose mandate was due to expire March 1987 but was recently extended for another year in light of the recent discoveries in HTSCs. In addition, the Ministry has established a new, three year project on HTSCs to start in April 1988. The Ministry is also planning on another project on applications of superconductivity. The Electrochemical Laboratory of the Ministry on International Trade and Industry has had a long history of developing superconducting magnets for magnetohydrodynamic generators and Josephson devices. About 30 scientists at

the Laboratory are now working on the new superconductors. In addition there are about 30 scientists and engineers at the National Institute for Research on Inorganic Materials and 50 at the National Institute of Metals also working on the new materials.

24. Japanese industrial efforts on HTSCs are also impressive. In materials development, Fujitsu is working on superconducting oxide coatings from binders. The Hayashi Chemical has achieved a production rate of 1 tonne per month for ceramic superconductors. Kyocera is also developing ceramics. Mitsui Mining and Smelting has achieved a a transition temperature of 99 K in a material through the addition of fluorine. Nippon Chemical is making coatings from organic binders fired at 800 C while Toyo Metal has produced a coprecipitation coating on aluminum wire fired at 350 C.

25. Electronics firms are also active. Hitachi has incorporated a thin film in an optical switch and is producing SQUIDs for medical use. Matsushita Electric is working on thin film production by means of magnetron sputtering at 650 C. NEC is investigating Josephson junctions for computers and the Sharp Corporation is looking at magnetic sensors for read/write heads.

26. In addition, a number of wire manufacturers are active: the Sanyo Electric Company has produced a 1 km long, 29 mil wire with a critical current capacity of 600 A/cm^2 at 77 K and Sumitomo Electric has achieved 32,000 A/cm^2 at 77 K in an interconnecting film and 1,240 A/cm^2 at 77 K in a silver enclosed wire. Japan seems to be well advanced in the field of HTSC. Over 300 papers on the new oxide superconductors appeared in the Japanese Journal of Applied Physics in the first 9 months of 1987.

Soviet Union

27. The USSR has long-term, aggressive programs in energy conservation, which include superconducting power transmission and energy storage, the fabrication of superconducting wires and tapes, electronics, particle beam collider construction, magnetically confined

magnetohydrodynamics and superconducting generators. Several Soviet laboratory contributions on the new HTSCs are appearing in the literature.

United Kingdom

28. The program of the U.K.'s Science and Engineering Research Council (SERC) will probably reach a funding level of $9.7 million U.S. over the first six years. It will concentrate on research into high T_c materials. In addition, the U.K. Department of Trade and Industry is establishing a collaborative three year program on superconductivity with funding expected to reach $14.5 million U.S. This program will likely be more applications oriented and will emphasize lower T_c materials than the SERC program. Seventeen companies have already either submitted proposals or expressed an interest. Electronics, electrical and engineering applications will be the main focus.

United States

29. The U.S. administration will soon introduce a package, entitled "The Superconductivity Competitiveness Act of 1987", in order to facilitate and speed the process by which U.S. leadership in science can be translated into commerce. The package is expected to concentrate on relaxing anti-trust provisions, providing greater patent protection to U.S. patent holders from foreign competition and to tighten provisions of the Freedom of Information Act. U.S. House representatives Don Ritter and Dave McCurdy are expected to introduce legislation recommending a five year program that would receive $120 million annually for superconductivity related activities. The current U.S. expertise in magnets using conventional superconducting materials was developed mainly in national laboratories. The large groups working on the new superconductors in the U.S. are associated with IBM, Allied signal, AT & T Bell Labs, Argonne, Boeing, Corning Glass, Du Pont, Exxon, Ford, General Electric, Hughes, Litton, Lockheed, 3M, Varian Associates and Westinghouse Sandia. Their work tends to be the most comprehensive and has produced the more interesting results with respect to fabricating wires, tapes, Josephson Junctions, thin films and SQUIDs. IBM has the largest ongoing corporate effort in superconductivity in the U.S.

TABLE 1 - APPLICATIONS OF SUPERCONDUCTIVITY

a. Small Scale Applications:

(1) Microelectronics
- (a) Josephson junctions
- (b) Battlefield medical diagnostic equipment
- (c) Guidance systems
- (d) High density integrated circuits (IC)
- (e) Inertial navigation systems [(NMR) gyros]
- (f) Millimetre wave gyrotrons
- (g) Mixers
- (h) Superconducting delay lines for communications and surveillance applications
- (j) Superconducting millimeter wave receiver - satellite communications
- (k) Standards for fundamental physical constants
- (m) Supercomputers

(2) Sensor technology
- (a) Biomagnetometer
- (b) Gravity gradiometer
- (c) Infrared detectors (bolometers)
- (d) Magnetic Anomaly Detectors (MAD)
- (e) Microwave detectors
- (f) Ordnance detection
- (g) Satellite surveillance
- (h) Square law detectors
- (j) Submarine detection
- (k) Superconducting quantum interference devices (SQUID)
- (m) Superconducting radiometer - millimetre/microwave surveillance
- (n) Target identification and selection

b. Large Scale Applications:

(1) Electromagnetic Propulsion
- (a) Accelerators
- (b) Motors and generators - smaller lighter ship drives

(c) Projectiles - rail guns
(d) Ships - magnetohydrodynamic (MHD) drive

(2) Energy storage devices
(a) Magnetic field energy storage
(b) Superconducting cells and batteries

(3) High density magnetic field transducers

(4) Magnetic levitation

(5) Magnetic, frictionless bearings

(6) Magnetic separation

(7) Medical apparatus
(a) Nuclear magnetic resonance (NMR) imagery
(b) Magnetoencephalography (MEG)
(c) Magnetomyography
(d) Electron spin resonance (ESR) imagery
(e) Magnetocardiography

(8) Robotics

(9) Shielding.
(a) Electromagnetic interference (EMI) prevention
(b) Electromagnetic compatibility (EMC) enhancement

(10) Transmission lines
(a) Low loss cables (for RF and other applications)
(b) Electrical power transmission

TABLE 2. - POSSIBLE TIME OF IMPLEMENTATION FOR VARIOUS SUPERCONDUCTING DEVICES

Application	K.Taschikawa Tokai Univ.	S. Tanaka U. of Tokyo	N. Makino Mitsubishi
Magnetic Levitated Train	2000	1995-2000	1995-2000
S.C.-Drive Ship	2000	1997	1990-1995
Power Line	1995-2000	2000	2000
Power Generator	2000	2000	1995-2000
Power Storage	2000	2000	1990-1995
Josephson Device	2000	1990-1995	1990
IC Package/ Substrate	1990	1990-1995	1990-1995
S.C. Semicon. IC	1990	1990-1995	1990
Magnetic Sensors	1990	1995-2000	1990
IR Sensors	1990	1990-1995	1990
Magnetic Shielding	1990-1995	now	1990-1995
Toys or Kits	1990-1995	1990	1990-1995
S.C. Magnet	2000	1995	1990-1995

From: Nippon Keizai Shimbun, 18 May 1987.

Applications of the new materials

30. Most of the applications that are envisioned for the new superconducting materials are extensions of devices or systems already explored or exploited with conventional superconductors operated at liquid helium temperatures. It may be, however, that the most important applications that will eventually evolve will employ new devices not yet contemplated. Applications generally fall into one of the two broad classes listed in Table 1. Predictions as to when applications will be available vary but the more optimistic positions indicate that within the next 10 to 15 years many should be realized. Table 2. presents the views of three leading Japanese researchers.

Impact on future capabilities

General

31. With the exception of high field magnets for use in nuclear magnetic imaging systems, small scale applications are expected to come to fruition first. Most quality electrical machines are already remarkably efficient at 98% to 99%. The use of superconductors to recover the 1% to 2% of the energy lost is generally not cost effective, especially if the capital investment for the new materials over conventional normal conductors is taken into consideration. There is also a considerable investment in conventional machines throughout the world and even if superconducting versions were available at competitive prices there would be no wholesale movement to replace everything. Conversion to superconducting systems would only be undertaken gradually by means of maintenance replacements. The main advantage for high energy applications, such as electrical machinery or power transmission, would be in reducing or eliminating the heat generated by losses associated with the conventional technology so that machines could be made smaller. It is estimated, for example, that electric motors, generators and transformers could be made about half the size and weight of current devices through the use of superconducting materials.

Commercial

32. High field magnets for imaging systems and research purposes are the main commercial uses of superconducting materials. Electronic systems using superconductors are perhaps the most promising applications for the new technology. Computer applications will have the greatest impact but will require more time to develop because of their complexity. Sensors and instrument applications will probably be commercialized within a few years. One electronics application, using conventional superconductors with liquid helium, has already found its way into a high speed oscilloscope . Use of HTSCs should reduce the cost considerably. Another application is in compact quantum interference devices (SQUIDs) for sensitive magnetic field measurements. Magnetometers have important uses in prospecting. Devices for measurement of fundamental physical constants and standards for voltage references are also important applications that could probably be realized much less expensively and made more widely available without loss of accuracy. Enhanced magnetic separation processes for metal extraction may also be possible. Finally, magnetic shielding is one of the simplest applications that could be exploited early.

Defence

33. Developing more sensitive magnetometers using SQUID technology at liquid nitrogen temperature appears to be one of the first applications of the new superconducting materials for defence. One might expect to see demonstrations of new magnetometers within one or two years followed in five years or so by development models of MAD equipment that use the new materials and are compact enough for helicopter borne submarine detection roles.

34. Superconducting bolometers offer the prospect of significantly enhanced infrared detectors with sensitivity in largely inaccessible wavelength ranges. This should result in much improved FLIRs and space based IR surveillance capabilities.

35. Millimetre wave devices for satellite communications, radar and surveillance applications, will benefit from superconducting millimetre wave gyrotrons, mixers, and delay lines.

36. Extremely accurate navigation systems, capable of extended periods of operation without external radio aids, will be needed for such systems as the nuclear submarines. Inertial navigation systems based on nuclear magnetic resonance gyroscopes using SQUIDs as detectors could provide the required sensitivity for rotation measurement and offer an attractive basis for a strapdown system of the future. NASA and DoD have supported work on superconducting gyroscopes for many years. The recent advances in superconductivity show excellent promise that it will be practical and cost-effective to develop highly reliable, accurate and long lasting gyroscopes for inertial sensor packages. In addition, the possibility of building ultra-stable clocks for space or communications offers improvements in such areas as electronic warfare, electronic support measures, and electronic counter measures.

37. If the limitations in critical current and the incompatibilities with silicon manufacturing technology can be overcome, higher density integrated circuits (IC) should become more feasible. One of the restrictions now is due to the heat generated in high density circuits. Superconducting circuits would not dissipate energy as heat. Supercomputers that could be held in the hand and have the power and speed of Cray machines seem possible and offer obvious defence capabilities in signal and image processing.

38. One of the most promising application areas is that related to 'medical diagnostics'. Advances in superconductivity will lead to refinements in NMR and MEG technology providing miniaturized, multi-channel instrumentation which will permit non-invasive monitoring of a wide range of body functions, dynamically and in real time. Measurement of metabolism in tissues and organs of the body could become possible, directly and automatically so that brain, heart and muscle functions could be monitored non-invasively in the field. Such enhanced development of magnetoencephalographic (MEG) techniques for non-invasive monitoring could enable assessment of human capability in operational environments. In the long term, advances in MEG technology may well eventually lead to 'thought control' of systems.

39. The non-invasive nature of NMR imaging systems could have direct benefits to the CF Medical Services. The new superconductors may make it possible to develop battlefield medical diagnostic equipment that is compact and portable. Not only could diagnoses and monitoring of patients be done non-invasively, but also remotely (no skin contact or body contact required). Casualties in adverse environments (NBC, cold weather, etc.) could be diagnosed or monitored without the removal of their protective garments. Magnetocardiography, magnetomyography and magnetoencephalography (to name a few) could even be performed as far forward as the first triage. There is, however, the problem of placing persons with wounds, containing metal shrapnel, in the intense magnetic fields of such systems. The magnetic fields could exert considerable force on any metal fragments within the body.

40. In the longer term, high energy, large scale applications should be possible, especially if room temperature superconductors are discovered. Electromagnetic propulsion using superconductors could provide enhanced performance for particle beam accelerators, electromagnetic launchers (rail guns), and even possibly magnetohydrodynamic (MHD) drives for ships and submarines. Practical, compact and powerful motors and generators for smaller, lighter ship drives are a more likely prospect and would probably appear first. Magnetic levitation and frictionless magnetic bearings could result in more efficient and quieter machinery. NASA is looking at magnetic braking of hypersonic aircraft and spacecraft during reentry in order to reduce aerodynamic heating so that ablative shield material may be reduced or eliminated from some of the vehicle surfaces.

41. Energy storage devices using superconducting magnets for load leveling and superconducting batteries offer prospects for new electrical energy sources. Similarly, superconducting transmission lines would make development of low loss cables for RF and electrical power transmission a possibility.

42. Superconducting materials provide the best electromagnetic shielding characteristics. Applications resulting from this property will be

particularly important to the defence field in areas such as prevention of electromagnetic interference (EMI), hardening against electromagnetic pulse (EMP) and transient radiation electronic effects (TREE), and enhancement of electromagnetic compatibility (EMC) for communications, surveillance and signal processing systems as well as mine hunting and possibly shielding of rail gun crews.

43. The use of superconducting materials for elements of short, high frequency (HF) antennas and microwave cavities should greatly improve efficiency. A recent application using superconducting microwave cavities for particle accelerators indicates that duty cycles could be raised from 1:1000 or 1:10,000 to almost 1:1 and that several million volts per metre accelerating voltages are possible. With higher temperature superconductors such devices would be considerably simpler to make and operate. Particle beam weapon and free electron laser development may benefit from this advance.

Possible initiatives for CRAD

44. It is very early to determine which applications will ultimately come to fruition and which will be blocked by serious problems. Much of what is known is not yet published due to the time lag between discovery and publication. There are also indications that details, especially those of fabrication techniques, may be being held back to protect commercial interests.

45. It will be important to stay in the game on a world wide basis in order to exploit developments in a timely fashion. We should begin our familiarization with this field now if we plan to exploit it fully when HTSC materials become available.

Close monitoring

46. As a minimum activity, staff should attend conferences and visit laboratories as much as possible in order to keep abreast of progress in this rapidly developing field.

Support of Canadian consortia

47. Experimental work should capitalize on existing expertise on a consortium basis with industry, universities, OGDs and agencies, etc. Actively supporting research work in the HTSC materials in bulk and thin film form, and in Josephson junctions and SQUIDs constructed from such materials would reap the greatest short term benefits. Efforts should be supported at more than a few universities and industries. Developing fabrication techniques and establishing good centres for characterizing the materials are two important areas to pursue. It would also be important to explore thin film devices such as SQUIDs and IR detectors (bolometers), and investigate heavy current applications.

Universities

48. A number of universities have formed loose cooperative groups to explore the new technology. With some funding from NSERC and contributions from various industries, the basis for a core of expertise is being established in Canada, but at a much smaller scale than elsewhere in the world. Nevertheless Canadians can make and have made significant contributions: namely, NRC's mapping of the crystal structure of the new materials and McMAster University's growing reputation as a centre of excellence in superconducting materials science. To the extent that CRAD could identify specific aspects of the technology that appear to have defence application, some contractual support to these consortia might be appropriate. As results become more promising, DSs might be seconded to such consortia as a form of sabbatical leave or alternatively arrangements could be made for an exchange of scientists if suitable programs could be worked out.

Selected Canadian companies

49. Canadian companies that possess expertise in superconductivity or have the potential to acquire it should be identified and supported early in developing defence applications of superconductivity. In many cases this would probably be accomplished by supporting various industrial university consortia.

In-house projects

50. In order to develop expertise and be able to position ourselves to address defence applications of the new superconducting materials, a number of in-house activities would be appropriate. For example, ideas received from the Research Establishments, CRAD/HQ and RMC suggested that it would be worthwhile to:

a. Demonstrate applications in MAD for helicopters.

b. Determine the feasibility of developing:

   (1) a superconducting gyroscope, and

   (2) a superconducting gravity gradiometer.

c. Improve DRE facilities and/or contribute to upgrading national characterization facilities in order that devices and applications using new superconductors can be evaluated for potential defence purposes. Devices for which facilities would be of particular interest include:

   (1) IR Detectors

   (2) microwave devices, and

   (3) magnetic detectors.

d. Investigate the possibility of using NMR imaging systems for diagnostic purposes on casualties working in a CW/BW environment. The new superconductors may make field portable systems feasible.

e. Examine, in the long term, the potential benefits of using superconductors for electrical power transmission in ship and submarine propulsion systems.

51. One possible approach to increasing involvement in the area would be to allow some reasonable percentage of the R&D effort to be put toward

superconductor related activities. NASA, for example, has allowed its centres to reprogram up to 15% of their budgets for research into HTSC materials for fiscal year 1988.

Conclusion

52. High temperature superconductivity is a major new advance in technology that has great potential in a wide range of areas. However, the prospects for success in developing the various applications are still unclear. Much has been discovered recently and it is expected that advances will be made rapidly over the next few years. Resolution of the critical current and stability problems might delay significant commercial use of the technology for some time. On the other hand, defence applications that rely on SQUIDs and superconducting magnets should appear relatively soon.

Acknowledgements

53. The contributions of the scientific staff of DGRD Ops and the DREs are gratefully acknowledged. In particular, the ideas provided by J.J. Grodski and Bob Angus and discussions held with Dr. S.M. Khanna were most useful. Mr. Ellington's editorial suggestions were much appreciated.

BIBLIOGRAPHY

Baird, D.C., Wright, L.E. and Batalla, E., RMC, Briefing to RDEC, CRAD Conference Room, 1 Dec 1987.

Beardsley, Timothy M., "Getting Warmer", Science and the Citizen, Scientific American, Oct 1987, pp 32 - 34.

Buttner, H. and Blumen, A., "Possible explanation for the superconducting 240-K phase in the Y-Ba-Cu-O system", Nature, Vol. 329, 22 Oct 1987, pp. 700 - 701.

Chu, F.Y., Ontario Hydro Research Division. "Recent Developments in High T_C Superconducting Material Research and Applications", NRC Division of Electrical Engineering, SCIENCE ASSOCIATION, 18 Nov 1987.

Clarke, John, "SQUIDs, brains and gravity waves", Physics Today, March 1986, pp 36 - 44.

Felici, R., Penfold, J., Ward, R.C., Olsi, E., and Matacotta, C., Determination of the magnetic penetration depth of the high-T_C superconductor $YBa_2Cu_3O_{7-x}$ by polarized neutron reflection", Nature, Vol. 329, 8 Oct 1987, pp. 523 - 525.

Forgen, Ted, "Superconducting ceramics: Finding characteristic lengths", Nature, Vol. 329, 8 Oct 1987, pp. 483 - 485.

Hayakawa, Hisao, "Josephson computer technology", Physics Today, March 1986, pp 46 - 52.

Hughes, David, "Pentagon Boosts Research Spending To Develop Practical Superconductors", Aviation Week & Space Technology, 16 Nov 87, pp 57 - 59.

Larbalestier, David; Fisk, Gene; Montgomery, Bruce and Hawksworth, David, "High-Field Superconductivity", Physics Today, March 1986, pp 24 - 33.

Lemonick, Michael D. Science, Time Magazine, 11 May 1987, pp 56 - 63

Manthiram, A. and Goodenough, J.B., "Synthesis of the high-T_c superconductor $YBa_2Cu_3O_{7-d}$ in small particle size", Nature, Vol. 329, 22 Oct 1987, pp. 701 - 703.

Maple, M. Brian, "Novel types of superconductivity in f-electron systems", Physics Today, March 1986, pp 72 - 80.

McKinnon, Ross, NRC. "High T_c Superconductivity in Perovskites", Ottawa-Carleton Institute Seminar, University of Ottawa, 1 Oct 1987.

Muller, K. Alex and Bednorz, J. Georg, "The Discovery of a Class of High-Temperature Superconductors", Science, vol 237, 4 Sep 1987, pp 1133-1139.

News, Physics Today, Jul 1987, pp 17 - 21.

News, Physics Today, Sep 1987, pp 51 - 54.

Nippon Keizai Shimbun, 18 May 1987.

Report of the Research Briefing Panel on High-Temperature Superconductivity, Committee on Science, Engineering and Public Policy, National Academy of Sciences, U.S.A., Oct 1987.

Richards, Paul L., "Analog superconducting electronics", Physics Today, March 1986, pp 54 - 62.

Robinson, Arthur L., "More Superconductivity Questions Than Answers", Research News, Science, Vol 237, 17 July 1987, pp 248 - 250.

Science and Technology, "Not-so-superconductors", The Economist, 13 June 1987, pp 93 - 99.

"Superconductivity - Defence Applications", DREO 3700-GE (ED) 20 Oct 1987.

"Superconductivity: Defence Applications", 3135-1 (DCIEM H/PPG) 22 Oct 1987.

"Superconductivity: Defence Applications", 3700-GE-1 (DREP) 29 Sep 1987.

"Superconductivity: Defence Applications", 3714-1 (Assoc DGRD Ops) 21 Oct 1987.

"Superconductivity: Defence Applications", 3714-1 (DREV 0100)/1355-1 9 Nov 1987.

"Superconductivity: Defence Applications", 3714-1 (DREV 1002) 23 Oct 1987.

"Superconductivity: Defence Applications", DREA 3700-1 14 Oct 1987.

"Superconductivity: Defence Applications", DREO 3700-GD (PSD/H/NES) 14 Oct 1987.

"Superconductivity: Defence Applications", DREO 3700-GE (ED) 23 Oct 1987.

"Superconductivity: Defence Applications", DRES 3135-3 (SSO/P) 22 Oct 1987.

Superconductor Week, Vol. 2, No. 1, 4 Jan 1988.

Superconductor Week, Vol. 2, No. 3, 18 Jan 1988.

Timusk, T. and Berlinsky, A.J., Institute for Materials Research, McMaster University, "High Temperature Superconductors", Physics in Canada, July 1987, pp 106-112.

Tinkham, Michael, "Special issue: Superconductivity 75th anniversary", Physics Today, March 1986, pp 22 - 23.

UNCLASSIFIED

SECURITY CLASSIFICATION OF FORM
(highest classification of Title, Abstract, Keywords)

DOCUMENT CONTROL DATA

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Establishment sponsoring a contractor's report, or tasking agency, are entered in section 8.)
Directorate of Scientific Policy
Research and Development Branch, Dept. Nat'l Defence
Ottawa, Ontario K1A OK2

2. SECURITY CLASSIFICATION (overall security classification of the document including special warning terms if applicable)
UNCLASSIFIED

3. TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C or U) in parentheses after the title.)

SUPERCONDUCTIVITY: RECENT DEVELOPMENTS AND DEFENCE APPLICATIONS (U)

4. AUTHORS (Last name, first name, middle initial)

MacPherson, R.W.

5. DATE OF PUBLICATION (month and year of publication of document)
March 1988

6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.)
27

6b. NO. OF REFS (total cited in document)
36

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

8. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include the address.)

9a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant)

9b. CONTRACT NO. (if appropriate, the applicable number under which the document was written)

10a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document.)

CRAD REPORT 1/88

10b. OTHER DOCUMENT NOS. (Any other numbers which may be assigned this document either by the originator or by the sponsor)

11. DOCUMENT AVAILABILITY (any limitations on further dissemination of the document, other than those imposed by security classification)

(x) Unlimited distribution
( ) Distribution limited to defence departments and defence contractors; further distribution only as approved
( ) Distribution limited to defence departments and Canadian defence contractors; further distribution only as approved
( ) Distribution limited to government departments and agencies; further distribution only as approved
( ) Distribution limited to defence departments; further distribution only as approved
( ) Other (please specify):

12. DOCUMENT ANNOUNCEMENT (any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution (beyond the audience specified in 11) is possible, a wider announcement audience may be selected.)

13. ABSTRACT (a brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), or (U). It is not necessary to include here abstracts in both offical languages unless the text is bilingual).

(U) The recent advances in superconductivity have led to much speculation about the possible applications of the new technology to all walks of life. In an attempt to determine what defence applications have realistic expectations of coming to fruition, a number of opinions solicited from defence scientists is summarized and reviewed along with information obtained from selected journal and magazine articles.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

Superconductors
Superconductivity
Defense systems
Research management
Military research
Reviews
Product development
Manufacturing
Stability
Microelectronics
Detectors
Electric propulsion
Magnetic properties
Magnets
Medical equipment
Shielding
Power transmission lines
Robots
Josephson junctions
Electric batteries